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Wind Tunnel Testing for a New Experimental Model of Counter-Rotating Wind Turbine

Lucia-Andreea Mitulet*, Gabriela Oprina, Rares-Andrei Chihaia, Sergiu Nicolaie, Adrian Nedelcu, Mihail Popescu

National Institute for R&D in Electrical Engineering ICPE-CA, 313, Splaiul Unirii, Bucharest, 030138, Romania

Abstract

The paper presents the achievements of INCDIE ICPE-CA on wind installations provided with counter-rotating turbines. There are envisaged both the development of an experimental model and the results following the testing activities, respectively. The experimental model submits a novelty technological character due to the unconventional innovative aspects. It represents a foregoing constructive version, preceding a wind turbine prototype with the rated power of 10-15kW designed for power autonomy assurance within specific applications.

The preliminary calculations, the numerical modelling of the wind rotors and the electric generator stand experiments have confirmed the energy conversion capacity for the double effect micro aggregate equal to 1kW for a 10 m/s wind velocity.

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Keywords: Wind turbine; counter-rotating electric generator; wind tunnel; experimental model; energy conversion

1. Current state of development in the field of counter-rotating wind turbines

The assessment of the energy production supplied by the conventional single rotors wind turbines has been extensively studied, the main objective being to increase the turbines' efficiency, as shown by [1]. A possible solution to be considered regards the use of two or more rotors and the suitable components (electric generators). In terms of the rotation direction, the research has been focused on two development directions: wind turbines with two

* Corresponding author. Tel.: +40.722.354.401
E-mail address: andreea.mitulet@icpe-ca.ro

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rotors with the same rotation direction and wind turbines with two rotors having opposite directions of rotation.

Counter-rotating wind turbines (CRWT) represent a system of two rotors which rotate in opposite directions – one rotor is rotating in clockwise direction and the other in counter-clockwise direction. For HA-CRWT (horizontal axis-counter-rotating wind turbines), the rotors are placed at a certain distance, either both in the front of the generator, or one in front and one in the rear of the generator. The performances of the counter-rotating wind turbines have been intensively approached within the last decade. Thus, some research is focused on numerical investigations of counter-rotating wind turbines, while others approach the study of CRWT both numerically and experimentally. The investigated systems enclose different generators' concepts: one generator for each wind rotor [2], one electric generator coupled to the rotors through a differential planetary system [3] or, such the case of the present study, a single permanent magnets generator, with mechanical coupling of the wind rotors [4]. Beside the other two solutions, the last one presents some advantages such as: decreasing the overall size of the electric generator, increasing the rotational speed, eliminating the mechanical power losses induced by the use of a gearbox.

In [3] is predicted, using the quasi-steady strip theory along with the experimental wake model obtained based on the wind tunnel test data, the aerodynamic performance of a 30 kW CRWT system, having the diameter of the up-wind rotor 5.5 m and the diameter of the down-wind rotor 11 m. The rotors, connected to the generator through a differential planetary system, were placed at different distances, starting from 1/8 to 1/2 from the diameter of the up-wind rotor. The performed analysis identified the relative size and the optimum placement of the rotors in the CRWT system - best performance was found to be at around one-half of the up-wind rotor diameter. In [5] is studied both numerically and experimentally a CRWT model having the rotors diameter of 0.8 m and the generator coupled to the rotors through a differential planetary system. In a wind tunnel were first experimentally investigated separately each of the rotors and then the counter-rotating operation of the two rotors. Trying to give a correlation between the operation of the CRWT system in a free stream and its operation in a wind tunnel, the blockage effects in the wind tunnel were numerically investigated using both a CFD model and measurement of drag coefficient. The results of the research showed that an increase of 9% of the maximum extracted power is obtained for the system compared to the single rotor case. Some studies [6], [7] numerically investigated the aerodynamic performance of the up-wind and down-wind rotors in order to obtain for each rotor the maximum energy that can be extracted from wind. The results of the CFD simulations performed for a 30 kW counter-rotating wind turbine were validated with experimental data from literature. The maximum power output of 90 kW was predicted at 14 m/s and the optimum axial distance between the two rotors was calculated at $0.65d$, where d is the diameter of the up-wind rotor. When the rotors are placed at this distance the maximum power increase is of 9.67%. The results showed a good correlation between the CFD simulations and the measurements, even though, in some conditions, the predictions were slightly bigger than the measured values. The interest in benefiting of the positive effects brought by the use of counter-rotating wind turbines has recently extended to wind farms, especially for onshore applications, due to smaller turbine spacing. Thus, in [8], [9], were experimentally investigated the positive effects of the relative rotation on the wake interferences for some models of stand-alone co-rotating wind turbines and stand-alone counter-rotating wind turbines of same diameter and having horizontal axis. The influence of the distance between the two turbines was also investigated and it was determined that for a spacing smaller than $2d$ the down-wind turbine in counter-rotating configuration produces at least 10% more power than the co-rotating turbine, while this benefit reduces to about 4% when the spacing increases to $5d$.

2. Design of new experimental model of counter-rotating wind turbine

The paper presents the achievements of INCDIE ICPE-CA on wind installations provided with counter-rotating turbines. This was accomplished by designing, manufacturing and testing of an experimental model with a rated power of 1 kW obtained for a 10 m/s wind speed.

In the design stage of the two rotors' blades, the following geometrical elements have been adopted (depending on the optimal availability in experimental model design stage):

-

- Up-wind rotor, shown in Figure 2 (Diameter D = 2.46 [m]): chord at the hub level c_{r0} = 0.15 [m]; chord at the blade's tip level c_R = 0.044 [m]; the blade's torsion angle Δβ = 15 [°]; blade profile type: EPPLER 664 extended.
- Down-wind rotor, shown in Figure 1 (Diameter D = 2.66 [m]): chord at the hub level c_{r0} = 0.1 [m]; chord at the blade's tip level c_R = 0.1 [m]; the blade's torsion angle 0 [°] (the blade has no torsion); blade profile type: NACA 6409.

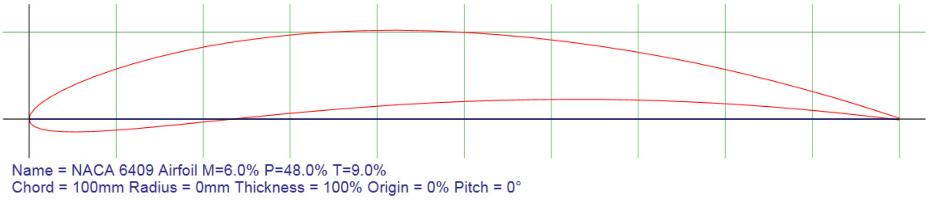

Fig. 1.NACA 7414 blade profile.

In order to determine the optimal distance between the two wind rotors, a SolidWorks simulation was performed using the Fluid Flow module. There was considered a reference length of the wake behind the upstream rotor of L=1.7 [m]. Thus, it was determined that the wake's maximum speed is reached at about 1 m from the rotor. By placing the second wind rotor at this distance, the maximum kinetic energy of the air flow can be extracted.

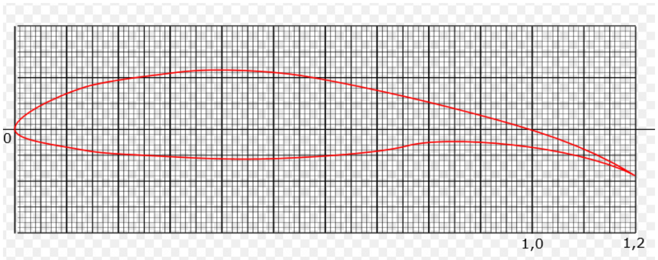

Fig. 2.Eppler 664 extended blade profile.

Based on the design calculations as well as on the performed experimental testing of the two wind rotors, there was established the technical theme elements [10]. Furthermore, a model of electric generator with counter-rotating armatures with 1kW rated power for a wind speed of 10 m/s has been developed.

For the construction of the electric generator, some parts from the current production of usual asynchronous motors have been used. The constructive solution is shown in Figure 3.

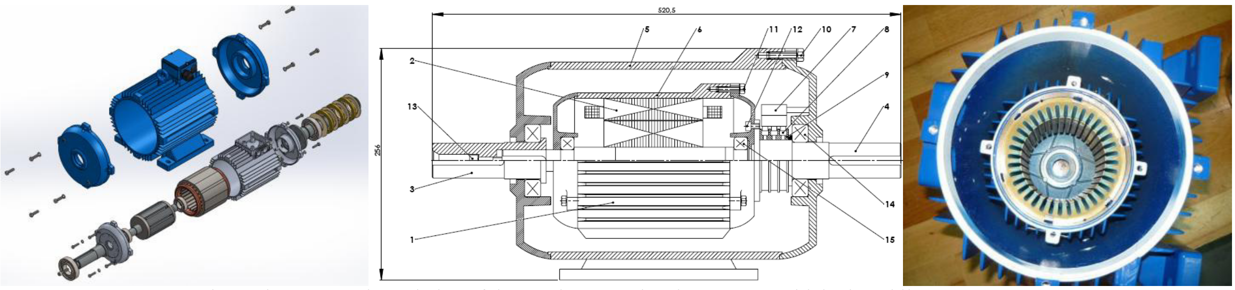

Fig 3. The constructive solution of the synchronous electric generator with both mobile armatures.
Components: 1 – rotor with permanent magnets, 2 – wound stator, 3 – rotating axis for rotor subassembly, 4 – driving axis for stator subassembly, 5 – outer casing (fixed), 6 – interior casing (mobile), 7 – trailer chassis, 8 – collector ring, 9 – insulating disc, 10 – M8 × 30 clamp.

The constructive design of the counter-rotating electric generator (the inductor and induced armatures can rotate independently) was achieved following a preliminary simulation of the generator's operation, performed using a FEM/FEA software (CEDRAT Flux 2/3D).

3. Wind tunnel testing of the experimental model of counter-rotating wind turbine

The experimental model of counter-rotating wind turbine was tested in a closed continuous circuit wind tunnel, which consists of an atmospheric pressure facility. Based on the data obtained from the conducted tests, there were plotted the torque characteristics, the mechanical output power at the turbine's shaft, and the electric output power for wind velocities up to 10.5 m/s (the maximum velocity that can be obtained in the tunnel's test section). The testing stand as well as an image of the counter-rotating wind turbine system placed within the testing section is shown in Figure 4.

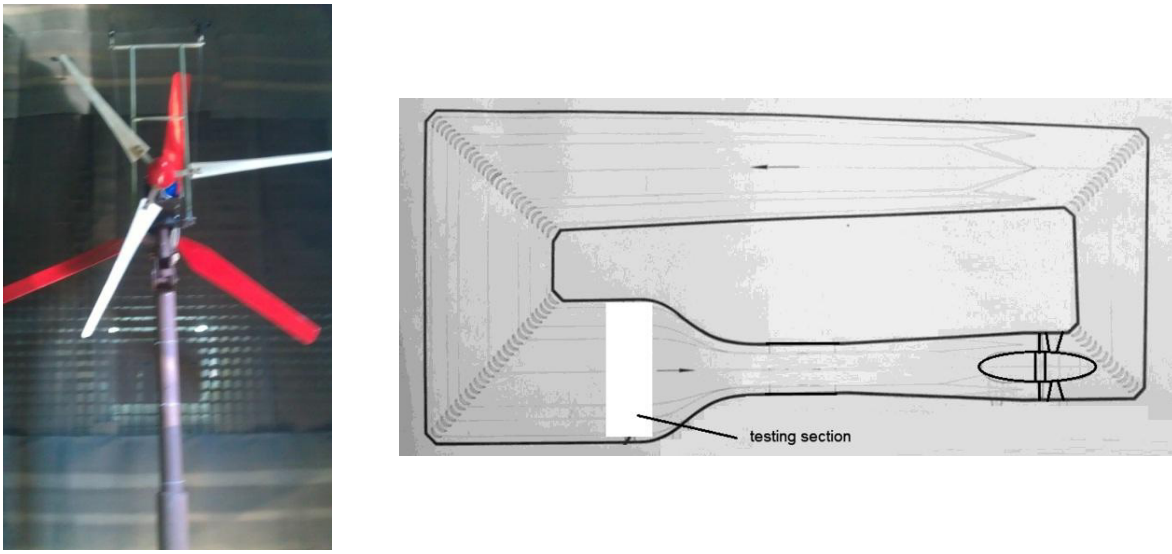

Fig. 4. The counter-rotating wind turbine system and the test section from the aerodynamic subsonic tunnel.

The mechanical loading of the two wind rotors was achieved by connecting several electrical resistances at the counter-rotating electric generator armatures. The electric generator characteristic was previously defined, in order to determine the comparative energy characteristic of the wind rotor as well.

4. Description of preliminary calculations for the counter-rotating wind turbine assembly

The measurements have been performed for different testing conditions, as follows:

- The up-wind rotor is in operation while the down-wind rotor was removed and the electrical armature shaft corresponding to the removed wind rotor has been blocked
- The down-wind rotor is in operation while the up-wind rotor was removed and the electrical armature shaft corresponding to the removed wind rotor has been blocked
- Both wind turbines are operating (counter-rotating regime).
  Based on the performed tests, there have been separately determined the characteristic parameters for each wind rotor as well as for the both wind rotors in counter-rotating operation

The following equations have been used for the determination of the main characteristic parameters:

- The angular speed:

$$\omega = 2\pi \cdot n / 60 \quad (1)$$

- The tip speed:

$$V_{tip} = \omega R \quad (2)$$

Where R represents the wind rotor radius; for the up-wind rotor R_f = 1.23m, while for the down-wind rotor: R_s = 1.33m.

- Tip speed ratio (TSR):

$$\lambda = V_{tip} / V_{wind} \quad (3)$$

- The theoretical power:

$$P = Cp \frac{1}{2} \rho A V_{wind}^{3}, \; A = \pi \cdot r^{2} \quad (4)$$

Where V_{wind} – the air flow velocity; ρ = 1,205 kg/m^3 at 20 °C;

- Power coefficient:

$$C_p = \frac{2P}{\rho A V_{wind}^{3}} \quad (5)$$

The first testing was conducted in the wind tunnel. These experiments focused on determining the energy contribution provided by the second rotor with similar diameter to the first rotor's diameter.

The preliminary results have been summarized in Table 1.

Table 1. Comparative data regarding the output power of the counter-rotating wind turbine vs. single rotor wind turbine.

Wind velocity [m/s]	5,5	6,3	6,88	7,74	8,7	10
P_{max} - Single rotor (up-wind rotor) [W]	98,12	148	192	275	388,84	591,13
P_{max} - Counter rotating turbine [W]	179,1	245	305	461,8	614,9	939,3
Output power increase [%]	**45,2**	**39,6**	**37,0**	**40,5**	**36,8**	**37,1**

As seen from Table 1, the average power increase is around 40% and has been determined for each specific wind velocity. The results clearly show the contribution of the second wind rotor which increases the energy conversion efficiency for the same given wind speed. However, in the future the authors will perform research activities related to the aerodynamically influence between the two wind rotors.

A second series of measurements have been performed by duplication of the characteristics on the testing stand. The experiments have been conducted by driving separately each end of the counter-rotating electric generator's shaft and by using two calibrated electric machines. Thus there have been achieved loading points similarly with those obtained within the wind tunnel. The sizes of the mechanical power at the two shafts have been determined, by using torque and rotational speed transmitters. By correlating the results obtained on both the testing stand and within the tunnel, there have been plotted the wind rotors characteristics Cp=f(λ).

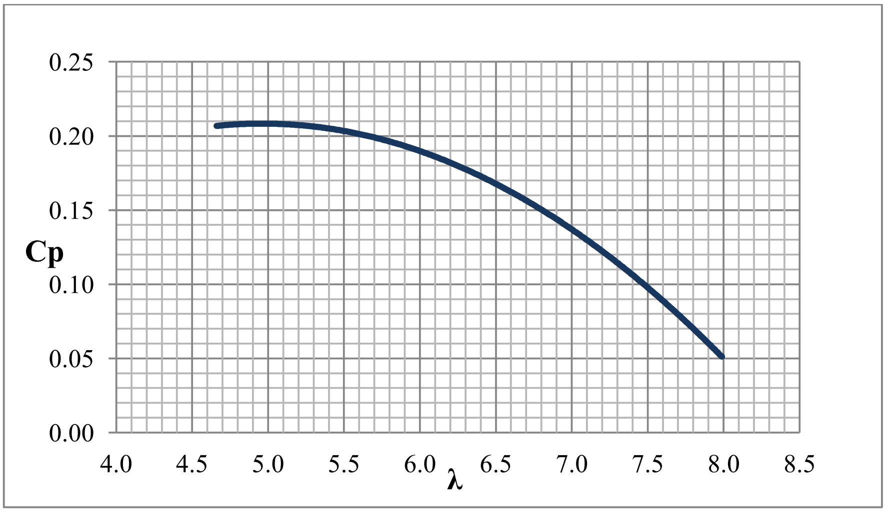

Fig. 5.Cp = f(λ) characteristic for the up-wind rotor.

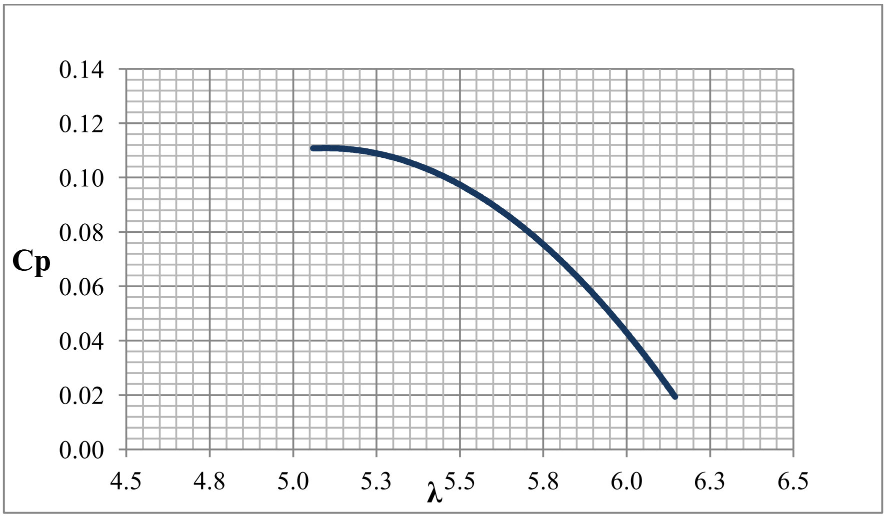

Fig. 6.Cp = f(λ) characteristic for the down-wind rotor.

Cp=f(λ) graphics have been used for plotting the characteristic curves for each turbine for a larger range of wind velocities and for several rotation speeds, respectively in order to separately characterize the wind rotors in individual operation.

In order to assure the optimum start-up operating conditions at reduced air flow velocities for the experimental wind turbine (with single rotor or both counter-rotating rotors), the attack angles of the blades were adjusted to a high value.

These measures regarding the start-up operating conditions justify the reduced values of the power coefficient for the wind rotors during operation, leading to a reduced aerodynamic efficiency of the entire wind system. Thus, sufficient energy potential is provided in the wake for the down-wind rotor. This additional kinetic energy provides higher energy values supplied by the counter-rotating wind turbine in comparison with single rotors wind turbines.

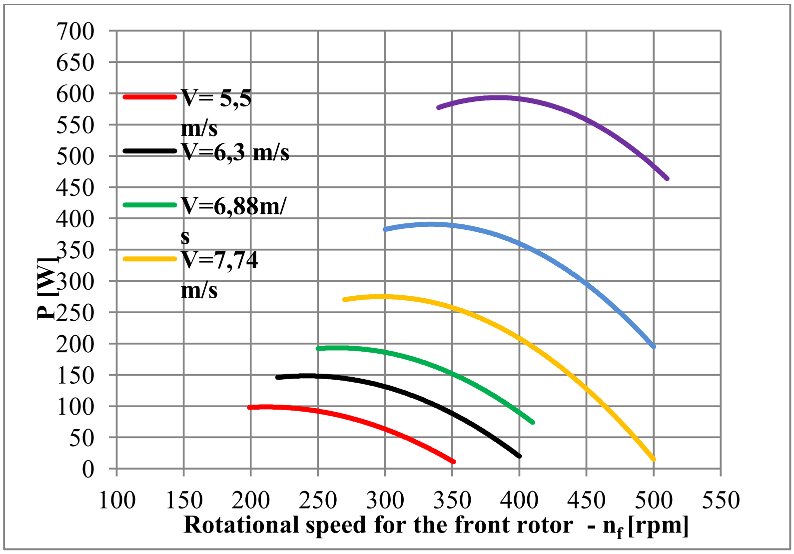

Fig. 7. Characteristic curves for the up-wind rotor P = f (n_f).

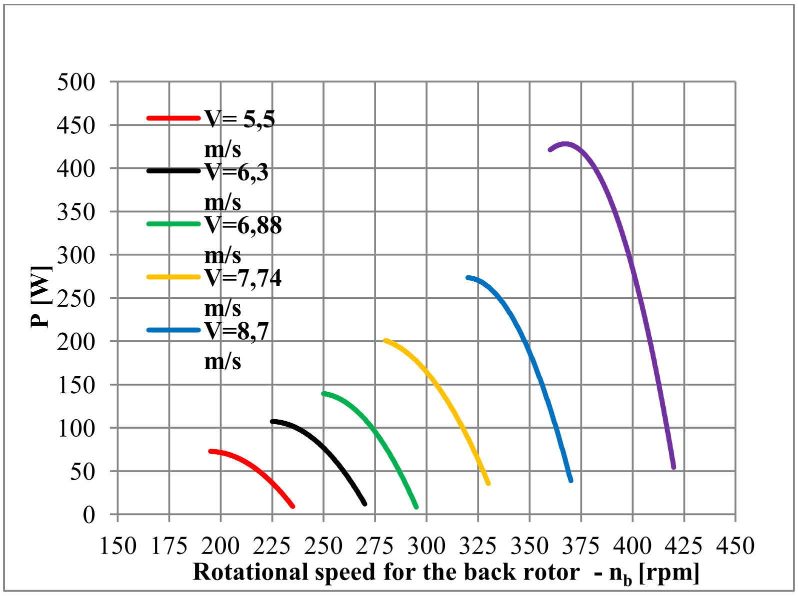

Fig. 8. Characteristic curves for the down-wind rotor P = f (n_b).

Some previous tests performed on a reduced experimental model of counter-rotating assembly have confirmed the theoretical prolusions (based on the action and reaction principle) that along the up-wind turbine – electric machine gap – down-wind turbine virtual axis, the mechanical torque remains constant. On this basis, there was introduced the wind turbine operation curve with the two rotors in counter-rotating regime.

The rotational speed was initially determined for exact torque values. On the same plot, there is shown the M=f(n) characteristic for both wind rotors.

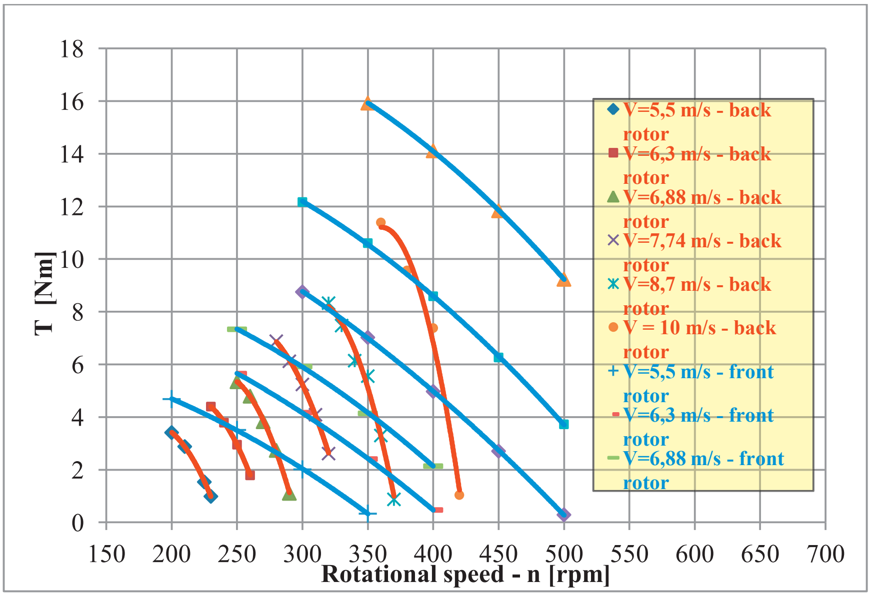

Fig. 9. Characteristic torque curves for both rotors at V = ct. - T = f (n).

The global characteristic of the corresponding electric power depending on the relative rotation speed between the generator's armatures (sum of the two turbines rotation speeds) is shown in the figure 10. Onto the same plot, there are presented the experimental curves along with those determined by calculation for the two turbines counter-rotating assembly. Based on the correspondence between the two types of curves, the approach following this procedure for the power characteristic predetermination can be enabled.

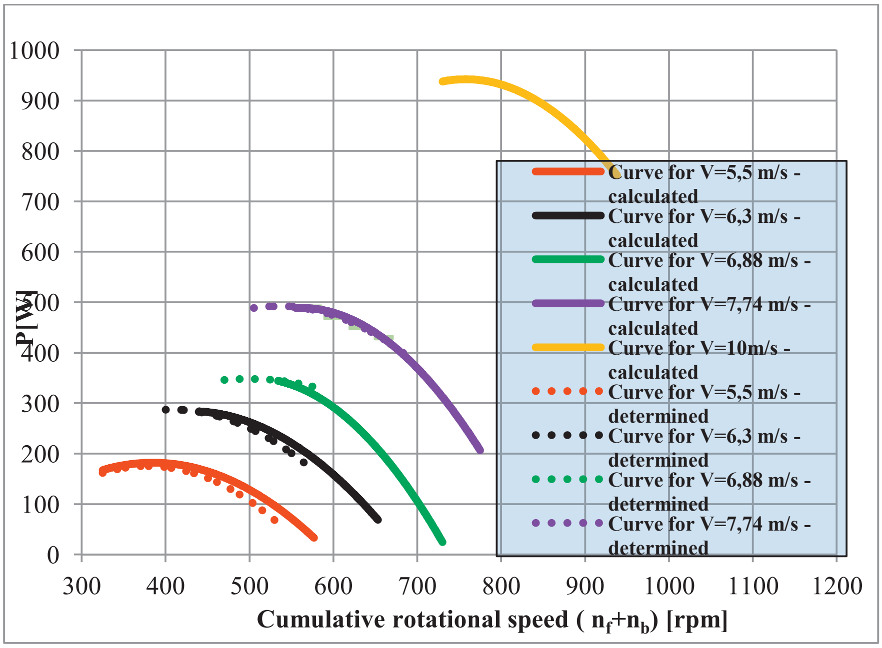

Fig. 10. Power curves P = f(n_f+n_b) at v =ct. - comparison between calculated data and determined data.

Conclusion

The paper objective is underlined by the necessity of increasing the maximum power which could be extracted from the air current by using counter rotating wind turbines. The conducted experiments have focused on the investigation of the energy contribution provided by a second wind rotor of a counter-rotating wind turbine system comprising rotors with similar diameters.

The analysis of the obtained results shows that the use of a second rotor contributes to the increase of the wind turbine extracted power by about 60% (on average) for the considered wind velocities and also for the selected attack angles of the wind rotors.

The performed tests have also confirmed the output power of 1 kW for 10 m/s wind velocity for the selected attack angles of the wind rotors, supplied by the developed experimental model of counter-rotating wind turbine. . It can be considered that the mechanical torque is constant along the turbine's virtual axis for the up-wind and down-wind turbine, and also along the air gap of the electric generator. Thus, there has been noticed a good consistency between the pre-calculated characteristics and the experimental determined sizes, resulting that the procedure is suitable to be further applied in designing a 15 kW wind turbine prototype.

Future plans will be focused on investigating the influence of the distance between the rotors on the total power which can be supplied by the wind system. Moreover, testing the wind system for wind velocities superior to 10 m/s must be considered. The optimization of the two wind rotors' attack angles in order to obtain a higher rated power of the system should be also taken into account. Furthermore, future investigations may regard as well a comparative economic analysis between the costs associated with the additional parts from the counter-rotating wind turbine assembly and the income resulted from the energy production provided by the second rotor.

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